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MAN/MACHINE INTERACTION IN ADAPTIVELY CONTROLLED EXPERIMENTAL CONDITIONS

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Systems in which a human subject interacts with an adaptive control mechanism through display and response facilities are examined. A cybernetic model is discussed, together with supporting experimental data.

1. *The Methods Used and the Form of Model*

1.1 *Experimental arrangement.* The subject is presented with a display consisting of two rows of eight signal lamps, the lamps in the lower row being in one to one correspondence with a row of response buttons. He is also provided with a particular one to one relation between lamps in the two rows which is intended to specify how any pattern appearing in the upper row should be transformed to produce a pattern in the lower row.

Stimuli are groups or patterns of signal lamps illuminated in the upper row. Given the nth stimulus pattern, the subject is required to respond by pressing a collection of response buttons that correspond to the transformed stimulus pattern and to do this within an interval of $\Delta t - \delta$, of about 5 secs, after the stimulus is displayed. His response is a correct response if and only if it correctly applies this transformation and is achieved within this interval. If it does not (or if the subject fails to respond) he is regarded as mistaken. In any case, at an instant $\Delta t - \delta$ after the stimulus is displayed, the correctly transformed stimulus is represented by a brief illumination of a pattern of

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lamps in the lower row of lamps and if the subject made a correct response selection this is indicated by an auditory signal. The stimulus pattern $n + 1$ is displayed Δt after the nth stimulus pattern.

The novice finds the skill impossible to perform when there are four lamps illuminated in each stimulus and when any one of up to 16 alternative patterns may be selected at a given trial. He says, in these conditions, that the problems posed by the stimuli are unintelligible. The skill can be simplified, however, by reducing the number of lamps from four to three or two or one and also by reducing the number of possible patterns. We denote the degree of simplification as μ and comment that it is possible to select a value of μ at which the novice finds the problems posed by the stimulus patterns intelligible and is able to start learning the "skill."

1.2 *Previous work.* Work since 1955 is reported by G. Pask (1957, 1958, 1960a,b, 1964a, 1965a), B. N. Lewis and G. Pask (1964), G. Pask and D. Wiseman (1959). The form of the coupled man/machine system is indicated in Figure 1. This diagram may be simplified by omitting the L^1 display and response board (IJ) and also the hypothesized representation of the human subject as an hierarchically organized adaptive control system by omitting the structure (α, β, γ). Here, Model 1 is defined with α, D, G, I, and J omitted, Model 2 with I and J omitted, and Model 3 as the complete diagram.

In most of this work, the external control mechanism has been designed to maximize the *rate* at which the subject (in this case a *student*) learns a skill (the performance of which is part and parcel of the experimental situation, where the display and response facilities act as a simulator for the skill). In a system of this kind we may thus regard the adaptive control mechanism as an adaptive teaching machine and its success in this capacity depends chiefly upon the accuracy and pertinence of additional assumptions that are introduced in order to provide a rate maximizing design (in other words, assumptions about the parameters and adaptivity of the hierarchical organization that represents the student). So far, our student models have emphasized the fact that a conscious man "needs to adapt" and most of them have explicitly embodied the more contentious supposition that a conscious man "needs to learn" (Pask, 1959, 1961a,b,c,d, 1962a,b, 1965b).

1.3 *Adaptive instruction.* In an adaptive teaching system of this sort the external machine senses the subject's performance and adjusts suitable parameters of the experimental (or skill simulating) situation to satisfy the following conditions:

(1) The problems denoted by stimuli are intelligible and potentially solvable.

(2) The sequence of problems offers the subject a sufficient variety or amount of novelty to occupy his interest and attention.

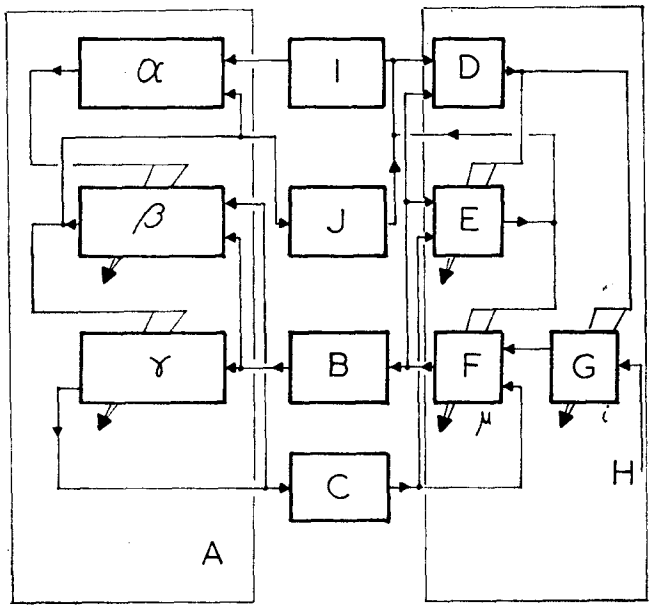

Figure 1. Models 1, 2, and 3. (In any first-order system the components D and G are omitted.) L^0 signs are stimuli or responses denoting problems and solutions; L^1 signs denote preference assertions and values of performance attributes.

A = The subject,
B = The L^0 display,
C = L^0 response board,
D = Computation of performance attributes,
E = Comparator for performance measure,
F = Problem simplification,
G = Problem type i,
H = Arbitrary input selecting problems,
I = The L^1 display,
J = The L^1 response board,
α = Methods for solution,
β = Adaptation,
γ = Solution procedures.

Since the subject's characteristics change as he learns, conditions of this sort can only be satisfied by an *adaptive* variation of the parameters and the external control mechanism can be regarded as *compensating* for the changes due to the learning process.

Relevant parameters have the form

(I) Degree of simplification or of partial solution of problems of a given *type*.

(II) Alternation of different types of problems or the probability that different types of problems will be posed or, finally, certain conditional and sequential attributes of the problems displayed.

When stimuli can be said to denote problems, when response alternatives can be said to represent solutions to these problems, when problem *type* and *degree* of simplification can be defined, we say that the skill is a "structured

skill" [the axiomatic statement of the conditions for a "structured skill" to exist is fairly elaborate (Pask, 1964b). One recent but rather restricted statement is given in Pask (1964c)]. All of our work on learning and teaching has involved "structured skills" or, at any rate, situations with a structure that adequately approximates the necessary set of constraints (indeed, an adaptive control mechanism can only be designed if a skill is a "structured skill").

The efficacity of an adaptive control mechanism is most legitimately (though not most dramatically) demonstrated by comparing the fully functioning arrangement with partially adaptive systems created by removing certain levels of control and replacing them by chance devices or routines. It is reasonable to suppose that these conditions are comparable (whereas it is not obvious that an adaptively controlled system can be legitimately compared with an arbitrary instructional paradigm). The data in Table I stems from

TABLE I

Values of T for Different Conditions A, B, C

T_A	T_B	T_C
150	180	130
170	210	140
190	220	150
190	230	190
220	250	240
220	270	290
250	310	320
260	330	320
260	350	360
270	350	390
290	370	430
290	370	430
290	370	450
300	390	470
310	410	490
310	420	500
330	440	510
360	460	510
380	460	530
440	470	570

Jonckheere's test of the null hypothesis, against the ordered *a priori* alternative of $T_C > T_B > T_A$, permits the null hypothesis to be rejected (in favor of the expected trend) at the 0.5% level of significance.

three different groups of 20 subjects each learning a selective skill and is expressed in terms of T, the number of trials needed to achieve a criterion performance of this selective skill. In condition A of Table I the student is instructed by a first-order controller that variably simplifies problems of different type and a second-order controller that alternates and rehearses the solution of problems of different type. In condition B the first order controller is preserved but the types of problem are alternated arbitrarily by a chance device. Finally, in condition C, the first-order controller is also replaced but, in this case, by a simple advancement routine.

1.4 *Cybernetic method.* Since the external control mechanism *compensates* for changes due to *learning*, it can be used in situations that do not explicitly involve instruction. It may even be usefully employed when the learning, which certainly occurs when a man perceives or acts or solves problems, is not immediately relevant to the experimental enquiry, for example, in psychophysics (Lewis, Pask, and Watts, 1964) and in visual discrimination experiments (Pask, 1964d). Indeed, the adaptively controlled experiment is the paradigm situation for a cybernetic experimental method in psychology (in the sense of a method that aims to *control* some feature of behavior or mentation and which models the subject according to the pragmatic tenets of effecting control). So far as learning *is* relevant in the experimental enquiry, this method was mentioned years ago by L. S. Vygotsky (1962) (that in order to measure the learning process it is necessary to mediate the control procedures of teaching and to detect the amount of cooperative assistance needed by each subject).

Our recent work stresses the broad concept of a cybernetic experimental method in psychology, used for the investigation of learning or other processes, rather than the relatively narrow idea of a teaching system. In this connection, our chief concern is the maintenance of the compensating interaction or, in other words, the stability of the coupled man/machine system (at least to the extent that this coupling, which involves the subject's attention to the displayed data, is adequately sustained).

1.5 *Basic stability.* A complete account of the stability conditions has not yet been attempted (we have only considered very special cases). But it is evident that any account will have at least a couple of logically separable components, namely (1) a structural component that depends upon the hierarchical structure of the organization representing the subject and the external control mechanism and (2) a statistical component concerned with the adaptive process at various levels in this hierarchical organization.

Thus, any talk about stability and, in particular, about a cybernetic experimental method presupposes an adequately defined structure, as in (1) above,

which can be identified with certain aspects of the experimental situation. Further, with reference to (2) above, it presupposes a statistical conservation principle that allows us to impose some kind of measure over the possible states of any one of the set of hierarchically arranged adaptive subsystems.

It has been argued that the structure is adequate for a discussion of stability insofar as it is possible to construct a hierarchically organized "artificial intelligence" problem solving program that is analogous to the possible learning processes (Pask, 1959, 1961a, 1964e). The levels in this hierarchy correspond to programming languages. The distinction between these levels is typified by the assertion that the lowest level is concerned with the solution of problems denoted by stimuli, through the application of operation processes derived from basic algorithms, in order to provide solutions; that the next highest level is concerned with the solution of problems posed by differences over the set of available lowest level algorithms to produce solutions that are novel members of this set of algorithms, and so on. Within this "artificial intelligence" system (or, of course, its logical equivalent such as the TOTE system cited by Miller, Galanter, and Pribram, 1960, or Miller and Chomsky, 1964), we conceive mentation as the application of operations (learning being reduced, as proposed by Newell and others, to problem solving in different domains).

Although we cannot, in a strict sense, define the motivational or volitional aspect of mentation within this structure (Pask, 1964e), it will be convenient to assume that we have specified, in one way or another, a restriction upon the amount of mentation that can and must occur. In particular (A) at a given level, there is a finite *maximum* rate at which operations can be applied and (B) over all the levels comprehended a definite *minimum* rate at which operations must be applied (a conscious man needs to learn; mentation cannot cease) (Pask, 1962a).

Now structural models of this kind can always be specified if a skill is a structured skill. In this case it is also possible to partition the mentation into a class that is, with reference to the structured skill (or experimental situation), relevant and goal-directed and a class that is irrelevant. Whereas, in consonance with the view that a conscious man needs to learn, our structural model must accommodate a minimum amount or rate of mentation, it is *not* necessarily true that this mentation is relevant and goal-directed. But we may regard an adaptive control mechanism that mediates a strategy that satisfies (1) and (2) in 1.3 as a device that, so far as possible, ensures that the necessary mentation *is* relevant mentation.

Now consider the analogous construction of a hierarchically organized pair of adaptive control mechanisms (one representing the subject and the other representing an adaptive device controlling the experimental situation).

The lowest level in this hierarchy is a single adaptive subsystem with the property that the subject component maintains a certain rate of adaptation and the external (or experimental control device) component provides conditions in which this adaptation can occur by using a strategy satisfying (1) and (2) in 1.3.

Within the structural framework it is legitimate to compute a variety or information measure of the relevant and goal-directed behavior and a redundancy $\lambda(n)$ of the relevant and goal-directed behavior at the nth trial in the experiment, which is a function of the subject's response selection and the degree of simplification assigned, at the nth trial, to the problems denoted by the stimuli he deals with by responding. Our adaptive condition is satisfied if $\Delta\lambda(n) > 0$ for all n or, if the trials are spaced Δt apart, and approximating if $\partial\lambda/\partial t > 0$ for all values of t. If this condition is satisfied, the coupled man/machine system is a self-organizing system in the sense of H. von Foerster (1960). For a large and plausible collection of substitution and application rules in the structural model it is not difficult to show that "$\Delta\lambda(n) > 0$" or "$\partial\lambda/\partial t > 0$" imply and are implied by the conservation rules (A) and (B) above and consequently that a self-organizing system has the statistical conservation property we require.

Among these systems there is an interesting subset with the further property that the adaptation rate is maximized when (in psychological parlance) the subject is maximally *loaded* (so that he is dealing with problems that are always as *difficult* or unsimplified as possible).

1.6 *Issues considered.* We shall indicate empirical data in support of certain contentions that stem immediately from these abstract models:

(1) The first-order adaptively controlled man/machine system of Model 1 is stable while it is a self-organizing system or broadly while the subject can maintain a positive $\Delta\lambda(n)$, $T > n > 0$ and has a predictable form of learning curve (Pask, 1964b,c).

(2) That in at least some first-order systems the learning rate estimated by $1/T$ is maximized by maximal loading (Pask, 1964b,c).

(3) Some higher order systems can only be stabilized if the subject and the adaptive control mechanism are allowed to interact at several levels of discourse (like L^1 shown in Model 3, which is a language of preference and performance property assertions) in contrast to the object language L^0 (with an alphabet of stimuli and responses) (Pask, 1964b).

(4) On the other hand, some systems can either be stabilized in the manner of Model 2 or of Model 3. If the L^1 facility *is* provided it is not appreciably used. The arrangement of Model 2 provides an adequate cybernetic model for the subject's learning process which *can* be represented by sequences of signs in L^0 (Pask, 1964c).

2. *Some Empirical Data to Support the Present Contentions*

2.1 *Simple stability.* In the first place, we need to show that the simplest kind of first-order system is stable, at any rate in the sense that a variation in the performance measure can be compensated by a variation in the degree of simplification. The data in Figure 2 are obtained from a system with a single

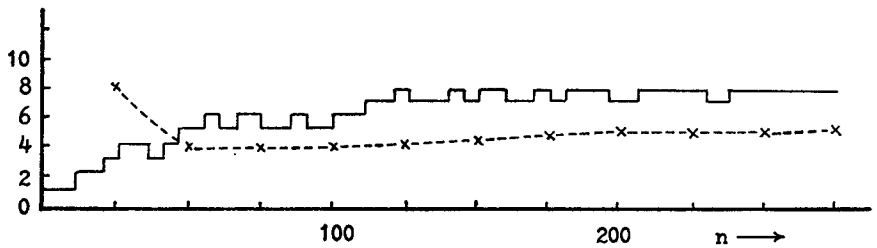

Figure 2. ———— $= \mu_{max} - \mu(n)$.
– – – – – $= \rho(n) \cdot 10$.

first-order parameter and demonstrate stability. In fact, these are the characteristics of a subject learning the selective skill of 1.1 in which he is given a rule and required to apply it to an arbitrary but variably simplified sequence of problems. The degree of simplification is interpreted as inversely proportional to the number of distinct elements in each problem. However, with a certain caveat (which we discuss later) the data in Figure 2 are typical for a large class of structured skills (of the kind that can be controlled by a first-order system) and the result is also typical of more elaborate systems wherein vectorial simplification procedures are used, one component procedure being assigned to each distinct class of mistake.

2.2 *Rate maximization.* For a subset of these structured skills man also acts as a device which adapts most rapidly when his input load is mantained at its maximum stable or intelligible value. We comment that this hypothesis is a consequence of assuming a simple reinforcement process as the basis for adaptation, given the constraints imposed by (A) and (B) of 1.5 above. However, it is also true that if the input load does approximate its stable (or intelligible) maximum value, then the number of mistakes made by the subject will be greater than they would be in less stringent conditions.

The data in Table II are derived from experiments in which A, B, and C denote different values of the adjustment coefficient.

$$\theta = \frac{-\Delta \text{ Degree Simplification}}{\Delta \text{ Proficiency Measure}}$$

TABLE II

Values of T and the Corresponding Values of Percentage Average Mistakes M for 12 Subjects

T_A	T_B	T_C	M_A	M_B	M_C
203	305	388	0.5	0.41	0.26
240	418	497	0.51	0.44	0.28
286	440	569	0.54	0.44	0.28
301	469	628	0.52	0.44	0.29
—	—	—	—	—	—
256	408	519½	0.52	0.44	0.28

The predicted trend of $T_C > T_B > T_A$ is significant at the 0.5% level using Jonckheere's trend test.

The predicted trend of $M_A > M_B > M_C$ is signified at the 0.5% level of significance using Jonckheere's trend test.

In this experiment condition A is more stringent than condition B and B is more so than C, in the sense that $\theta(A) > \theta(B) > \theta(C)$. Further, if $\theta > \theta(A)$ the problems posed become unintelligible for most subjects.

We thus predict that M (the average number of mistakes) will satisfy $M_A > M_B > M_C$. Next, assuming that the adaptation rate is maximized at the maximum input load and using T as an inverse measure of adaptation rate, we predict that $T_C > T_B > T_A$.

These predictions are adequately supported by the data from Table II and we comment that similar results have been obtained for all of the first-order controllable and structured skills so far considered (this picture of things appears to be applicable unless there is interference between the component "subskills" of a structured skill or, equivalently, between learning to solve different "types" of "constituent" problem). The result is not necessarily contrary to the Skinnerian paradigm (1959) given an adequate interpretation of "reinforcement."

2.3 *Larger organizations.* Higher order systems in which the interaction between the acquisition of an ability to perform each of the subskills (or to solve each of the types of problem) is limited to a positive transfer of training and simple interference are also stable and conservative in the broader sense that variations in the value of the performance measure or of any degree of simplification parameter can be compensated by a variation in another "available" degree of simplification parameter. The data shown in Figure 3 are derived from a Model 2 second-order system in which the subject is learning a skill made up from eight different subskills. The skill, in this case, is predictive. The subject is required

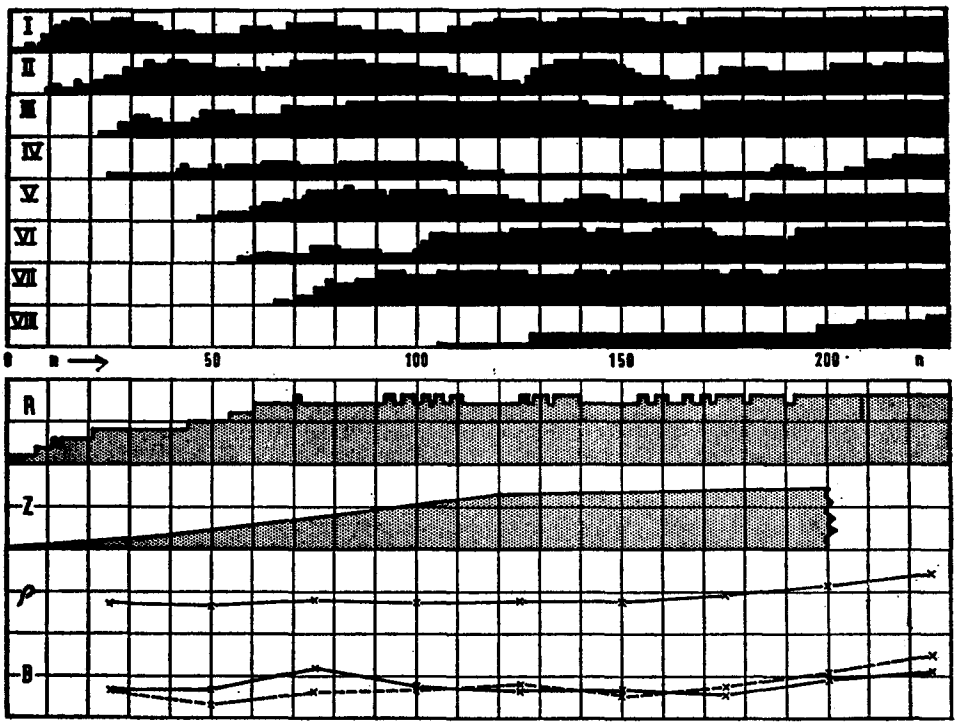

Figure 3. Characteristics of a coupled system used for instructing a structured discrimination skill having eight different subskill problem types.

n = Number of trial. I...VIII = $\mu_{max} - \mu_I(n) \ldots \mu_{max} - \mu_{VIII}(n)$.
R = Number of elements in subset from which subskills are selected.
Z = Sum of the averages of the eight different subskills.
ρ = Proficiency measure defined as $\rho(n) = (1/R) \sum_i \rho_i(n)$.
B = Proficiency measure with reference to rapid and less rapid predictions. (See Pask, 1965a)

to detect visually displayed trajectories against a background of visual "noise." The eight subskills correspond to eight different classes of trajectory and the degree of simplification (which is separately adjusted by the first-order adaptive control mechanism for each subskill) is interpreted as inversely proportional to the "noise" amplitude. The second-order adaptive control mechanism adjusts the number of alternative trajectory classes from which a particular trajectory is selected (by an arbitrary input) for presentation at the nth trial. Hence the number of "available" degree of simplification parameters depends upon the value of n. This number is shown in Figure 3 as $R(n)$ and $Z(n)$ denotes the sum of the averages of the eight difficulty values. The fact that $Z(n)$ is a number increasing with $R(n)$ and the fact that the value of $Z(n)$ is

increasing when the performance measure is essentially constant are taken to support the existence of a statistical conservation principle. These data are typical of a group of 15 subjects (in the sense that the relations between $Z(n)$, $R(n)$ and the performance measure are preserved for all members of this group) (Pask, 1961–1965).

2.4 *Participant modes.* Returning to our caveat of 2.1, we shall briefly consider the characteristics of systems which fail to exhibit the stability cited as normal in 2.1 (systems which exhibit oscillatory characteristics). For first-order systems about 10% of the subjects demonstrate oscillatory instability and for higher order systems the percentage of subjects showing this form of first-order instability is much greater.

When the detailed records are scrutinized the fluctuations appear to be due to specific sequences of mistakes, for example, sequences in which the subject makes a single kind of mistake. Many of the subjects agree that this response mode is deliberate and that it is intended to modify the characteristics of the adaptive control mechanism. Since there is no provision within the object language, L^0, for higher order preference assertions of the kind needed to induce such a change, the subject uses the only method available (which amounts to a misuse of L^0, since the response signs in L^0 are supposed to be identified with the solutions for problems posed by L^0 stimulus signs). We call this mechanism the "participant" mode of interaction (although, in the case we have cited, it is "participation due to a misusage").

If participant interaction is responsible for the first-order instability, it should be possible to remove it by introducing delays or chance events that prevent the subject from correlating his deliberate mistake sequences with subsequent changes in the degree of simplification. This prediction has been experimentally verified for first-order systems. The record from a previously instable system with interpolated delays or chance events is stable and detailed scrutiny fails to reveal any response sequences of this idiosyncratic kind.

However, a higher order system may become completely instable if participant interaction is disallowed. In view of our artificial intelligence hypothesis this is not altogether surprising. Consequently we have investigated the converse of preventing participant interaction, namely, of providing L^1 channels as in Model 3 along which the subject can make L^1 assertions of preference and receive indications that denote attributes of his performance. These "metasystems" (Pask, 1964f) have been examined experimentally in some detail but (apart from commenting that, in higher order systems, the organization of a "metasystem" is often needed to achieve stability) we shall not discuss the issue further in the present account.

2.5 *Further investigations.* Since data of the kind we have considered can

be obtained for many subjects and a large number of structured skills (or experimental situations) it seems fair to maintain that there *is* a method of adaptively controlled psychological experiment. Insofar as we *also* accept the more abstract comments of 2.3 and 2.4, this method is more than a procedure for approximating stationary-state measurement. It gives rise to a definite class of models associated with a further class of testable hypotheses. Although we have not exhibited the point in the present discussion, hypotheses derived from the artificial intelligence model can be tested according to detailed criteria (concerning *how* the subject learns and what problem solving procedures he adopts and what *concepts* he constructs).

At the moment we are developing this experimental method in various ways. Some of this work refers to teaching (the adaptively controlled instruction of skills) but most of it deals immediately with the process of mentation. At one extreme the method is being applied to concept learning and creativity, intermediately, to a measurement of fluctuations in attention and, at the other extreme, to an investigation in the field of psychophysics.

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